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Review of solar air collectors with thermal storage units

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ABSTRACT

Thermal energy storage is one of the most efficient ways to store solar energy for heating air by energy collected from sun. The relative studies are involved to the type of collection with the type of storage, i.e. separated to each other or integrated. This review summarizes the previous works on solar air heaters with storage materials include greenhouse, encapsulation, and the latest development in the solar thermal energy storage with air as a heat transfer fluid. The recent researches focused on the phase change materials (PCMs), as latent heat storage is more efficient than sensible heat storage. It has been appeared that PCM with high latent heat and suitable geometry are required for optimum thermal performance of solar air heater. The recent designs of solar air heaters with thermal storage units reduced the cost and the volume when integrated in one product.

Contents

1. Introduction

Energy storage is not only plays an important role in conservation the energy but also improves the performance and reliability of wide range of energy systems, and become more important where the energy source intermittent such as solar. Energy storage process can reduce the rate mismatch between energy supply and energy demand. The thermal energy storage can be used in places where there is a variation in solar energy or in areas where there is a high difference of temperature between day and night. In field of solar heating systems, water is still used as a heat storage material in liquid based systems, while a rock bed is used for air based system, but when you compare the volume requirements for the storage of heat energy between water and phase change material like Glauber's salt, you will see that the water heat storage requires almost five times amount of space as the Glauber's salt heat storage, this space savings would result in reduced costs for insulation and construction. The applications of solar energy to heat the fluids can be used to heat buildings, drying vegetables, fruits, meats, eggs incubation, and other industrial purposes [58], the air heaters are classified according to their applications and use as shown in Fig. 1.

The latent heat method of storage and their materials that have been studied during the last forty years have been reviewed recently by Farid et al. [2] these are usually hydrated salts, paraffins, non-paraffins, fatty acids and euctectics of organic and non-organic

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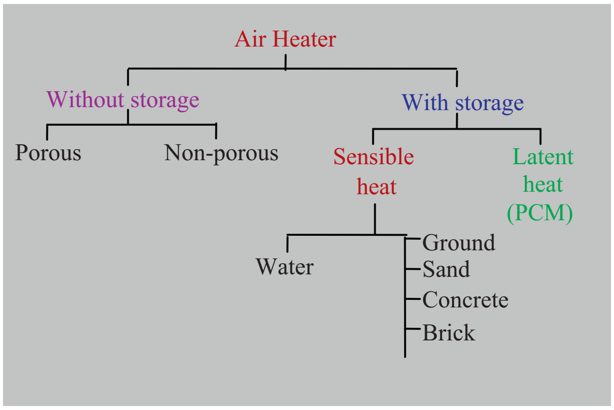


Fig. 1. Classification of solar air heater [1].

compounds. Khanna [3,4] described an arrangement for heating with solar energy by means of a heat exchanger and storage coupled to the two water heaters, and studied design data for solar heating of air using a heat exchanger when the heat transfer by both natural and forced modes, It was found that the data would assist in obtaining the final design of a shell-and-tube heat exchanger for use in drying a specific material and space heating of a living room. Ayensu and Asiedu-Bondzie [5] constructed a dryer with thermal storage unit from local available materials. The system was capable to transferring 118 W m^2 to a hot air.

2. Space heating systems with storage units

The solar collection system determines the temperature at which the storage material will be charged and the maximum rate of charge. Thermophysical properties of the storage material at this temperature are important in determining the suitability of the material. For example, flat plate liquid type collector may use water as the storage material, while air type flat plate collectors for space heating may use a rock or pebble bed as the storage medium [6].

A theoretical model is developed by Morison and Abdel-Khalik [7], for studying the transient behavior of phase-change energy storage (PCES) unit and studied the performance of solar heating systems using both air and liquid as working fluid. They had used these models in conjunction with simulation techniques to determine the relative effects of storage size, location, and collector quality on the performance of heating systems with sensible or latent heat storage. According to their simulations, they found that systems with $Na_2SO_4{\cdot}10H_2O$ have slightly higher f (fraction of load supplied by solar source) than those with the same mass of paraffin wax, provided that the thermal properties of the salt do not degrade from the cyclic operation of the system.

Jurinak and Abdel-Khalik [8], have presented a simple empirical method for sizing phase-change energy storage units for air-based solar heating systems for many locations during heating seasons, the previous studies used the solar collector and PCM units separately. Ghoneim [9] has studied the effect of assumptions in the models of earlier studies on both the fraction of the load met by solar energy, and the required storage capacities and noted the similar results as in Ref. [8]. Sokhansan and Schoenau [10] have achieved a simulation for a system consists of wall solar air collector, thermal storage, and building ventilation system, the water used as a storage material for both sensible and latent heat, analyzed the collector and storage costs, it is recommended that 15 kg of water be used per unit area of collector, and simple payback period was 4–5 years.

An experimental and theoretical investigations of latent heat storage for a water solar heating system is work performed by Kaygusuz [11], the system was designed to heat a laboratory building, and consisted of a solar collector, an energy storage tank, a water-to-air heat exchanger, an auxiliary electrical heater, a water circulating pump and measuring and The collected solar energy was transferred to the storage tank which contained polyvinyl chloride tubes with 1500 kg of calcium chloride hexahydrate. Whenever the space heating load was required, it was satisfied using the energy storage tank and the auxiliary energy source. During the heating season, the measured values of the mean collector and storage efficiencies were 0.60 and 0.70, respectively, with the 30-m^2 water solar collector used in the system. The solar-supplied fraction in the load was not as high as the collector and storage efficiencies for the same collector with the PCM, and its maximum value was around 0.30–0.35 because there were several days with cloudy conditions.

Mehmet [12] designed a system consists of a solar collector (30 m^2) connected to a cylindrical latent heat storage tank was filled with 1090 kg encapsulated PCM ($Ca_2Cl_2{\cdot}6H_2O$) linked to a solar powered heat pump used for space heating, this system works with two modes, one when no solar energy or weak, the cold water goes to the storage unit to extract the heat, while the other mode when there is a solar energy and the space heating load is zero the hot water circulated between the collector and PCM tank. Arkar and Medved [13] were studied the design of latent heat storage with small polyethylene spheres encapsulated PCM, which forms porous media inside the duct of the building ventilation system. In this study they assumed that ambient air is first heated in solar roof, then passes through latent heat storage and at the end enters into living spaces as preheated ventilation air, they concluded that, the heat storage size optimization should be made for the seasonal period and not only for chosen typical days. In that case also radiant cooling in summer nights could be analyzed while the measurement results for solar roof show that the ambient air could be cooled for 3–4 K in a clear summer night.

Analytical equations were presented by Xiao et al. [14] to calculate the optimal phase change temperature and the total amount of latent heat capacity and to estimate the benefit of the interior PCM for energy storage. Results show that; the optimal phase change temperature depends on the average indoor air temperature and the radiation absorbed by the PCM panels. Some recent applications in heating of buildings, the containment of PCM can become an integral part of the roof, but does not absorb solar energy directly as shown in Fig. 2.

Saman et al. [15] analyzed the thermal performance of a phase change storage unit as a component of a roof integrated solar heating system. The unit consists of several layers of phase change material (PCM) slabs with a melting temperature of 29 °C. Warm air delivered by a roof integrated collector is passed through the spaces between the PCM layers to charge the storage unit, similar as shown in Fig. 2. The stored heat is utilized to heat ambient air before being admitted to a living space. The study is based on both experimental results and a theoretical two dimensional mathematical model of the PCM employed to analyze the transient thermal

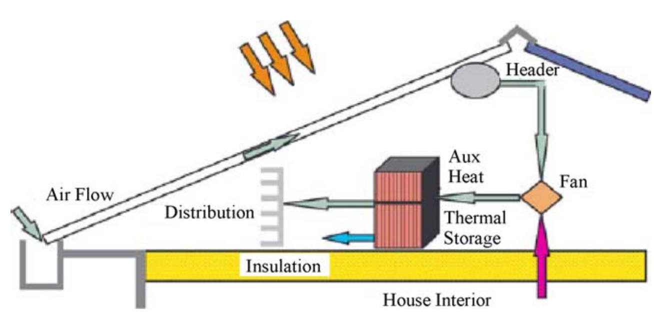


Fig. 2. Roof integrated solar heating system with storage unit [16].

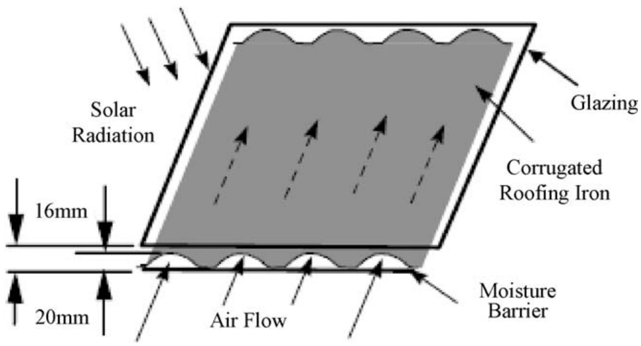


Fig. 3. Glazed roof integrated solar air collector [16].

behavior of the storage unit during the charge and discharge periods. The results are compared with a previous analysis based on a one-dimensional model which neglected the effect of sensible heat. A comparison with experimental results for a specific geometry is also made.

UniSA (University of South Australia) [16] has developed a roof-integrated solar air heating/storage system, which uses existing corrugated iron roof sheets as a solar collector for heating air. A PCM thermal storage unit is used to store heat during the day so that heat can be supplied at night or when there is no sunshine. The system similar to Fig. 2 operates in three modes. During times of sunshine and when heating is required, air is passed through the collector and subsequently into the home. When heating is not required air is pumped into the thermal storage facility, melting the PCM, charging it for future use.

Belusko et al. [17] used a corrugated steel roof to function as an unglazed air collector, roof insulation and a moisture barrier placed under the roof (Figs. 2 and 3). Their investigations were concerned with phase change materials that were fabricated into 2 kg fibre boards manufactured by Rubitherm GmbH, Germany. The product has a fusion temperature of 40 °C, storage capacity of 100 kJ/kg and costs around 0.72 US$/kg. The average daily winter heating load is approximately 70 MJ, which amounts to a weight of 700 kg and a volume of 2 m^3.

The performance of the system only generated 9% savings relative to a heat pump. Without glazing the analysis suggested the performance was too low to generate any meaningful savings, but further research is needed to fully confirm this finding.

3. Heat transfer in packed bed and capsules

3.1. Packed bed storage

In using a packed bed for solar energy storage, heated air flows from solar collectors into a bed of graded particles from top to which thermal energy is transferred during the charging phase. The recovery of this stored energy is usually achieved by reversing the air circulation flow through the bed. Some desirable characteristics; good heat transfer between air and solids promotes thermal stratification. Due to poor heat exchange by conduction between the rocks, the stratification is maintained over reasonably long time intervals. One limitation of stratified rock bed system is that it cannot be charged and discharged simultaneously. Therefore a large load draw in the day time causes a drop in temperature of air outlet from solar collector which will now have air inlet at ambient temperature and must meet the entire load by itself since the storage cannot supply a part of the energy requirement when collector is operative. However, the stratified rock bed system is as effective as similar water storage for night time delivery to the load [18]. Ayensu [19] designed and constructed a solar dryer with a rock storage system. It was found that the rock pile stored enough energy to enhance nocturnal drying. The duration of crop drying in the solar dryer was shorter than that in the open air.

The standard storage capacity of a solar air heater is 0.25 m^3 of pebbles (including void space) per unit area of the collector [20]. Butler and Troeger [21] have experimentally evaluated a solar collector-cum-rock bed storage system for peanut drying. The drying time from 22 to 25 h to reduce the moisture content from 20% to the safe storage moisture level with an air flow rate 4.9 m^3/s. Choudhury et al. [22] studied the optimization of design and operational parameters of a rock bed thermal energy storage device coupled to a two pass single cover solar air heater, i.e., charging time rock bed size, cross-sectional area A_R, the void fraction, and air mass velocity per bed cross-sectional area (G), this optimization has been achieved by investigating the previous parameters, he found that when designing and operating of rock bed, the (G) value and A_R should be selected depending on the requirement of temperature for any particular application.

Chauhan et al. [23] studied the drying characteristics of coriander in a stationary 0.5 tone/batch capacity deep-bed dryer coupled to a solar air heater and a rock bed storage unit as shown in Fig. 4 that is to receive hot air during sunshine and off-sunshine hours, respectively. The theoretical investigation was made by writing the energy and mass balance equations for different components of the dryer-cum-air-heater-cum-storage and by adopting a finite difference approach for simulation. The results revealed that for reducing the moisture content 28.2% (db) to 11.4% (db) the solar air heater takes 27 cumulative sunshine hours, i.e. about 3 sunshine days, whereas the solar air heater and the rock bed storage combined take 31 cumulative hours, i.e. about 2 days and 2 nights at an air flow velocity of 250 kg/h m^2, and recommended that the heat stored in the rock bed can be used effectively for heating the inlet (ambient) air for off-sunshine drying of agricultural products.

Tiwari et al. [24,25] have experimentally evaluated a crop dryer cum water heater and crop dryer rock bed storage (Fig. 5). They reported energy balance equations for each component of the system have been used to predict the analytical results. On the basis

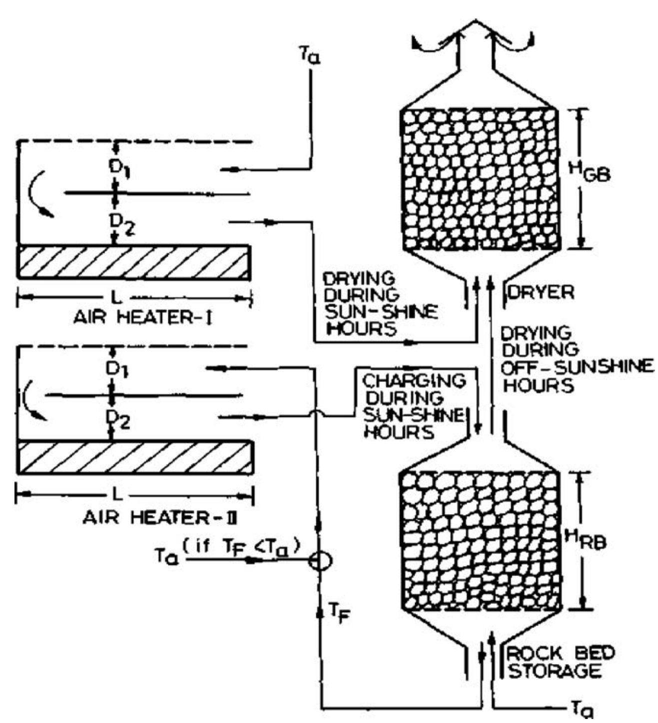


Fig. 4. Air heaters with rock bed storage [23].

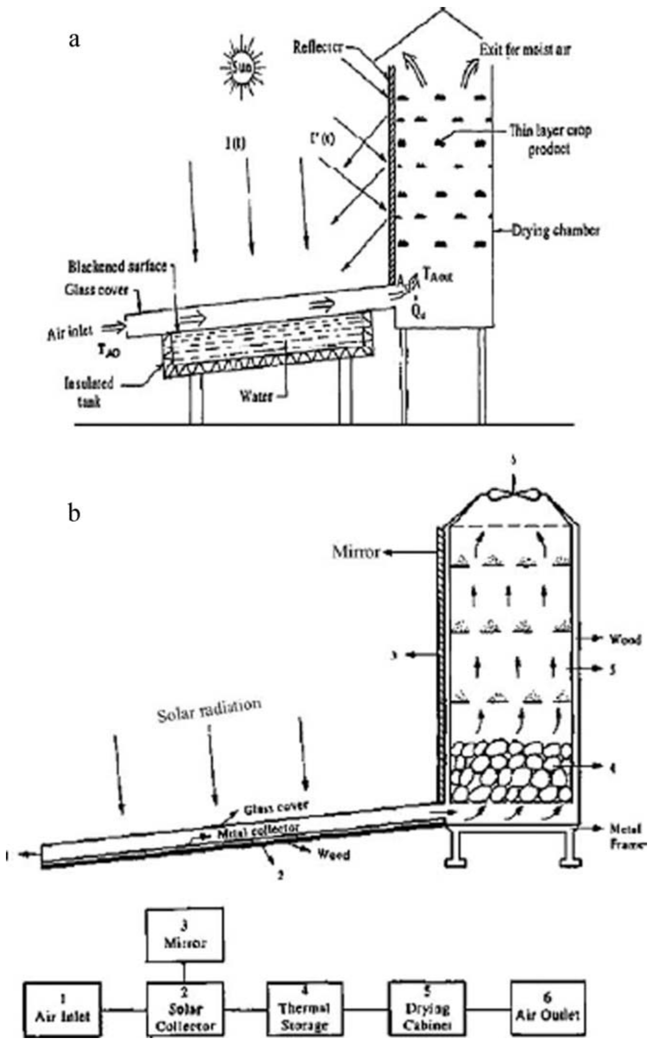


Fig. 5. Cross-sectional view of the crop dryer: (a) with cum water heater [24] and (b) with rock bed storage [25].

of the analytical results, it is observed that the drying time is significantly reduced due to the increase in thermal energy on the collector by the reflector. The system can be used to provide hot water in case the drying system is not in operation. The water heater below the air heater systems will act as a storage material for drying the crop during off-sunshine hour.

Amer et al. [26] designed and constructed a hybrid solar dryer consists of solar collector, reflector, heat exchanger cum heat storage unit and drying chamber. Under Mid-European summer conditions it can raise up the air temperature between 30 and 40 °C above the ambient temperature. Using the water tank with the solar dryer, about 15 °C can be stored in water during the time of sunshine. During the night, the system transfers the stored heat from the water to the air inside the solar dryer and controls the air temperature through the drying process at night, and observed that the drying air temperature rose from 25 to 35 °C above the ambient air and the drying time was about 10 h.

3.2. Heat transfer studies in phase change problem

The low thermal conductivity represents the common problem to PCMs, several methodologies have been reported in the literature based on the theoretical and experimental investigations to enhance the heat transfer by using fins of various configurations Lacroix [27], Veraj et al. [28], Shatikian et al. [29] or by saturating porous metals with PCM, Shiina and Inagaki [30]. And impregnating a porous graphite matrix with PCM [31–35].

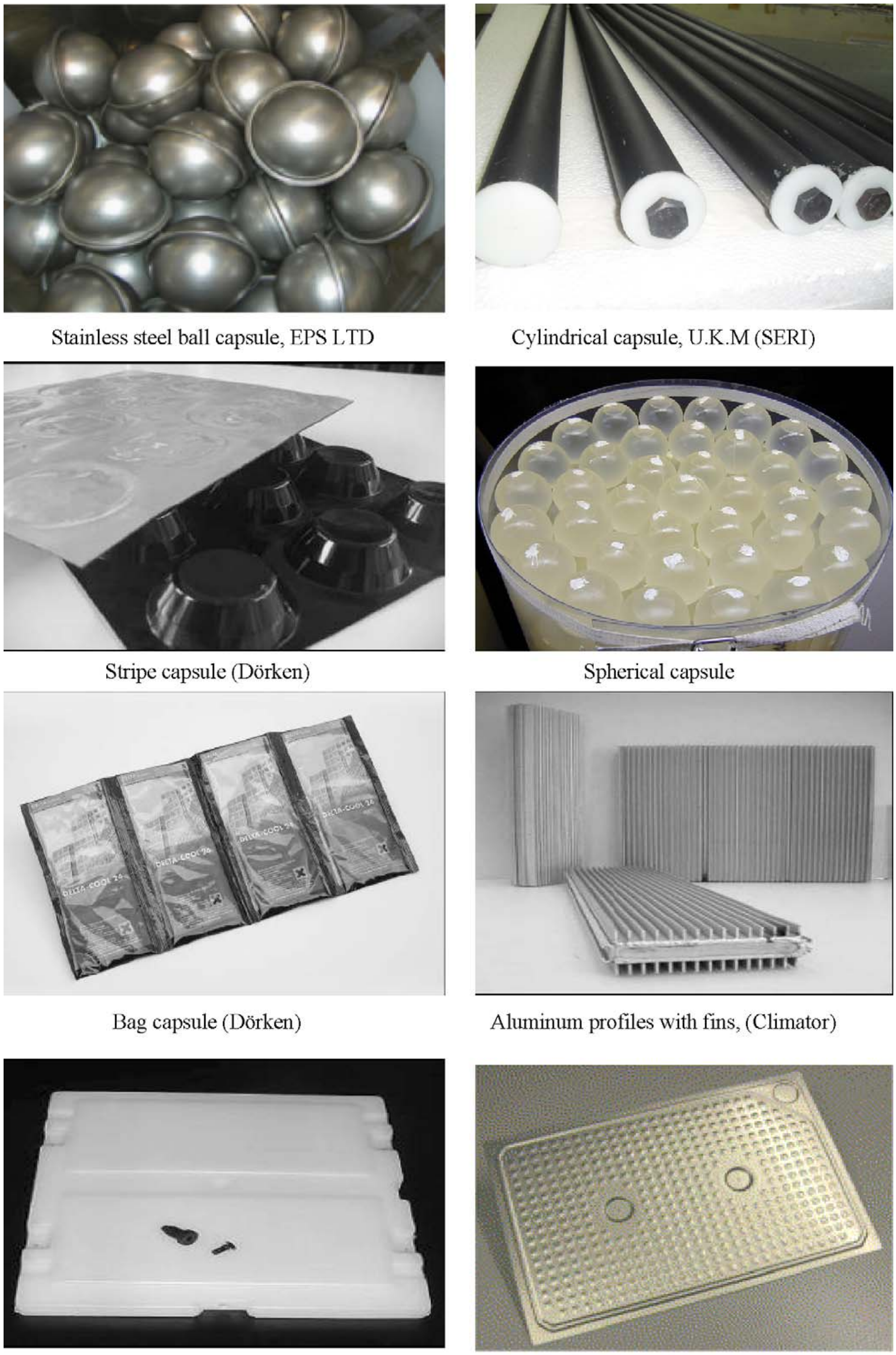
Some of researchers used high thermal conductivity additives like aluminum powder and graphite-PCM composite material, Marín et al. [36], and Mettawee and Assassa [37] who investigated a method of enhancing the thermal conductivity of paraffin wax by embedding aluminum powder in paraffin wax with a water base collector. The time wise temperatures of the PCM were recorded during the processes of charging and discharging. It was found that the useful heat gained increased when adding aluminum powder in the wax as compared to the case of pure paraffin wax. The geometry of PCM container and its material also related directly to the heat transfer from the PCMs to the air.

3.3. Heat transfer studies in capsules of various geometry

Encapsulations usually classified by their size into macro- and microencapsulation. *Microencapsulation* is the encapsulation of solid or liquid particles of 1 μm diameter with a solid shell. Physical processes used in microencapsulation are spray drying, centrifugal and fluidized bed processes, or coating processes [38]. A large improvement in the heat transfer rate was obtained by encapsulating the PCM in small plastic spheres [39,40] to form a packed bed storage unit. However, the expected high pressure drop through the initial cost may be major drawbacks of such units.

Macroencapsulation means filling the PCM in a macroscopic containment that fit amounts from several ml up to several liters. These are often containers and bags made of metal or plastic [38], as shown in some examples in Fig. 6. The advantage of the macroencapsulation is that the possibility to apply with both liquid and air as heat transfer fluids and easier to ship and handle. Lane [41,42] has identified over 200 potential phase change heat storage materials melting from 10 to 90 °C to be used for encapsulation. Macroencapsulation of $CaCl_2 \cdot 6H_2O$ in plastic film containers appears promising for heating systems using air as the heat transfer medium. He has assessed the technical and economic feasibility of using encapsulated PCMs for thermal energy storage in solar driven residential heating applications and has developed means of encapsulating a group of promising phase change heat storage materials in metal or plastic containers. After considering a number of heating and cooling schemes employing phase change heat storage, a forced hot air, central storage design using $CaCl_2 \cdot 6H_2O$ encapsulated in plastic pipes was adapted [2].

Many studies on air as a heat transfer fluid with a storage material encapsulated in various geometry. Solomon [43], predicted the behavior of an array of PCM cylinders as a storage unit in crossflow of pumped air, and recommended to use this method to design the systems and their simulation. Benmansour et al. [44], investigated experimentally and mathematically both charging and discharging processes using paraffin wax as a storage medium encapsulated in spheres inside a cylindrical tank, from this study, they concluded that the developed numerical model has shown that significantly accurate prediction of the temperature distribution within the bed during both charging and discharging is possible. Arkar and Medved [45] achieved mathematical modeling for charging and discharging of thermal energy from paraffin (RT20) encapsulated in spherical capsules in a cylindrical tank. Discharge process from ammonium alum/ammonium nitrate eutectic has been investigated by ratio. The rate of PCM temperature change was also investigated, and it was found that for their application on average it does not exceed 0.1 K/min. Only during sensible cooling of the liquid paraffin and the sensible heating of solid paraffin did the rate of temperature change reach value of 0.2 K/min. but their application did not enable an experimental verification at a higher rate of temperature change.



Stainless steel ball capsule, EPS LTD

Cylindrical capsule, U.K.M (SERI)

Stripe capsule (Dörken)

Spherical capsule

Bag capsule (Dörken)

Aluminum profiles with fins, (Climator)

Flat container (Kissmann)

Plate (Rubitherm Technologies GmbH)

Fig. 6. Photographs of macroencapsulation of various geometry [13,38,57–59].

Jotshi et al. [46] investigated mathematically and experimentally both charging and discharging for ammonium alum/ammonium nitrate eutectic, used spherical capsules inside a cylindrical tank. Adebiyi et al. [47] used zirconium oxide, copper as a storage medium encapsulated in cylindrical pellets in a cylindrical tank, investigated both charging and discharging processes for high temperature mathematically and experimentally, can be use this study for flue gas and air.

Adebiyi [48] studied charging and discharging processes in PCM (IGT) as a storage material and achieved some mathematical modeling. One major conclusion of the study from both the first-law and second-law perspectives is that the principal advantage in the use

of phase-change storage material is the enhanced storage capacity, compared with the same size of packed bed utilizing a sensible heat storage material.

Farid and Husian [49] achieved an experimental investigation and mathematical modeling for charging and discharging processes in the commercial paraffin wax encapsulated in cylindrical tubes in a horizontal duct under a natural convection of air of larger units. Ettouney et al. [50] investigated experimentally both melting and solidification for paraffin wax encapsulated in spherical shell when the air was a heat transfer fluid.

Shiina and Inagaki [30] investigated experimentally and mathematically melting time for storage medium; water, octadecane, Li_2CO_3, and NaCl, improved the thermal conductivity by saturating porous metals with PCM encapsulated in cylindrical capsules, where air, helium and water used as a HTF. Kuznik and Virgone [51] investigated experimentally melting process for *n*-octadecane storage medium encapsulated in spherical capsules when the air was a direct HTF.

Silva et al. [52] investigated experimentally and mathematically melting and solidification of paraffin wax in a vertical rectangular enclosure, when the HTF was the air, they concluded that the correlations developed can be used for the rapid estimation of the charge and discharge times and so can be useful in the design of this kind of latent-heat thermal-energy store. A good amount of work has been devoted to investigate the performance enhancement by employing multiple PCMs in different configurations of LHTS units.

Farid and Kanzawa [53] employed three PCMs of different melting points packed in cylindrical capsules. Air was used as HTF. During both charging and discharging about 10% increase in heat transfer rate was obtained with three PCMs as the melting/solidification started in all three PCMs simultaneously, where as in single PCM system the phase change process started at different times.

Farid et al. [54] constructed a latent heat storage module consisting of 45 cylindrical capsules fixed vertically in 15 rows. The capsules made of copper tubes 0.335-m long and external diameters of 31.8 mm were fixed in an insulated rectangular duct. Three commercial waxes having melting temperatures of 44 °C, 53 °C, and 64 °C were selected. Each of the three sets of 15 tubes was filled with different wax. For comparison purposes, experiments were also done with a single commercial wax, having a melting temperature of 53 °C, in all the tubes. During heat charge, hot air flowed across the capsules such that the melting temperature of the waxes decreased in the flow direction. Air flow direction was reversed during heat discharge. Experimental measurements showed some improvement in the heat transfer rates during both heat charge and discharge when three types of PCMs were used. There was no improvement in the heat transfer rate during the sensible heat storage period, while a maximum increase of 15% was observed during the latent heat period. Theoretical predictions [53] for the performance of the storage module were in reasonable agreement with the experimental measurements. Table 1 presents the summary of the studies carried out on air as HTF with various geometry PCM capsules.

Table 1
Heat transfer studies on storage units with air as HTF.

References	System geometry	Storage medium	Operation mode	Nature of Work	Remarks
Solomon [43]	Array of cylinders in a duct	Sodium sulfate decahydrate and other salts	Discharging	Experimental/Mathematical	Melting point (T_m) = 12.8 °C
Benmansour et al. [44]	Spheres inside a cylindrical tank	Paraffin wax	Charging and discharging	Experimental/mathematical	$T_m = 60\,°C$, $560 < R_e < 1120$
Arkar and Medved [45]	Spherical capsules in a cylindrical tank	Paraffin (RT20)	Charging and discharging	Mathematical	$50 < \dot{m}_f < 220\ m^3/h$
Jotshi et al. [46]	Spherical capsules in a cylindrical tank	Ammonium alum/ammonium nitrate eutectic	Charging and discharging	Experimental/mathematical	$491 < R_e < 531$, $T_{initial}$: 65 °C
Adebiyi et al. [47]	Cylindrical pellets in a cylindrical tank	Zirconium oxide, copper	Charging and discharging	Experimental/mathematical	$200 < \dot{m}_f < 600$ kg/h
Adebiyi [48]	Cylindrical pellets in a cylindrical tank	PCM (IGT)	Charging and discharging	Mathematical	$\dot{m}_f = 0.59$ kg/s
Farid and Husian [49]	Cylindrical tubes in a horizontal rectangular duct	Commercial paraffin wax	Charging and discharging	Mathematical	$0.007 < \dot{m}_f < 0.04$ kg/h
Ettouney et al. [50]	Spherical shell	Paraffin wax	Melting and solidification	Experimental	$4 < V_f < 10$ m/s
Shiina and Inagaki [30]	Cylindrical capsules	Water, Octadecane, Li_2CO_3, NaCl	Melting	Experimental/mathematical	$300 < R_e < 7500$
Kuznik and Virgone [51]	Spherical capsules	*n*-Octadecane	Melting	Experimental	$150 < R_e < 1800$
Silva et al. [52]	Vertical rectangular enclosure	Paraffin wax	Melting and solidification	Experimental/mathematical	$\dot{m}_f = 0.005488$ kg/s
Farid et al. [53,54]	Cylindrical capsules fixed vertically	3 commercial waxes	Charging and discharging	Experimental/mathematical	T_m = 44 °C, 53 °C, and 64 °C
Fang and Chen [55]	Shell and tubes	Arbitrary and paraffin waxes	Charging	Mathematical	T_m = 20–80 °C
Domanski and Fellah [56]	Cylindrical tubes	2 kinds arbitrary	Charging and discharging	Mathematical	For best 2nd law efficiency T_m for downstream $\approx T_{ambient}$

4. Greenhouse systems

Greenhouse production systems were originally implemented in cold regions at northern latitudes in order to extend the production season of plants, where usually they will not grow optimally. However, current controlled environment agriculture (CEA) industries operate in different climate regions throughout the world, including semiarid and tropical regions [60]. Generally the greenhouse system can be considered as a large solar thermal collector,

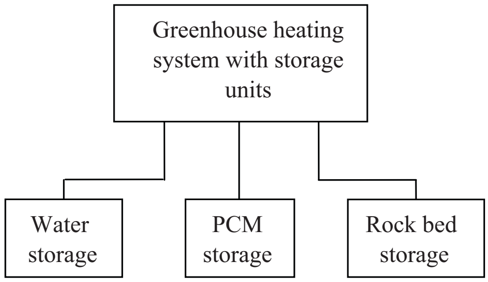


Fig. 7. Classification of various thermal storage methods in the greenhouse heating system.

the researchers found one alternative and clean way to achieve the heating needs instead of conventional fossil fuel usage, are by using the natural solar energy and store thermal energy, called Solar Thermal Energy Storage.

4.1. Greenhouse heating system with storage units

The greenhouse heating system with storage unit is used to increase the thermal energy storage inside the greenhouse during the day and to transfer excess heat from the greenhouse to the heat storage unit. This heat is recovered at night to satisfy the heating requirements of the greenhouse. The most important existing greenhouse heating systems with storage unit are use: water storage, rock bed storage and phase change material storage classified as shown in Fig. 7.

The heat storage medium can be placed outside the greenhouse or can also be placed on the surface that is also exposed to the incident solar radiation or it can be placed underground, the information related to our work in Tables 2–4 have been reported by Sethi and Sharma [121] in their survey.

4.1.1. Water thermal storage system

In this type of heat storage, Water filled in plastic bags and ground tubes can be placed inside the greenhouse between the rows of plants or used water tanks/barrels along the side of the greenhouse which face the solar radiation act as a large solar collector integrated with storage material [61]. The collection of solar energy is achieved through plastics tubes filled with water and laid on the ground between the rows of plants Underneath the water tubes a black polyethylene (PE) film is laid to collect the solar radiation, volume of water stored in the bags was 10 m^3, it was found that, the system was able to maintain 2–4 °C higher inside air [61].

Gupta and Tiwari [62] predicted the room air temperature, storage water temperature and the thermal energy storage effect of a water mass in a low cost, they used A metallic water tank of diameter 0.55 m and height 0.90 m, painted black as thermal storage unit placed at the center of about 21 m^2 greenhouse. It has been observed that (i) there is a significant thermal energy storage effect of the water mass on room temperature and (ii) thermal load leaving, which is found to decrease with an increase in the mass of storage water, varies with month of year. An experimental validation of the developed model has also been demonstrated. The predicted room and water temperature show agreement with experimental values.

Sethi and Sharma [121] in their survey reported that Montero et al. [63] studied a greenhouse used a storage tubes placed along the pathways between the plant rows in a 72 m^2, single (PE) covered greenhouse Total volume of the water was 1.5 m^3. Inside room air temperature was maintained 2–4 °C higher than the outdoor conditions during winter nights in Spain (12.2 °C in January, 24 h average).

4.1.2. Rock bed thermal storage

Although the rock bed represents a sensible heat storage material, used widely due to the economical property is used generally as an air-based thermal energy storage material. The performance of heat storage in a rock bed is affected by various design and operational parameters such as rock size and bed, air mass flow rate, void fraction within rock bed, thermal and physical properties of rock. Table 3 summarizes the performance of various greenhouses using rock bed as heat storage material.

4.1.3. Phase change material storage

Phase change materials have also been used in green houses to storing the solar thermal energy for curing and drying process and plant production [92]. When the ambient temperature drops below the phase change temperature, the PCMs solidify, releasing stored heat. PCMs can store 5–14 times more heat per unit volume than conventional storage materials and can also be more long term.

Table 2
Summary of the performance of various greenhouses using water storage systems [121].

Reference	Storage container	Cover material	Volume stored (m^3)	Volume per unit area (1 m^{-2})	Performance
Montero et al. [63]	Ground tubes	PE	1.5	20.83	2–4 °C higher
Kyritsis and Mavrogianopoulos [64]	Ground tubes	PE	5.0	33.33	2–4 °C higher
Von Zabeltitz [65]	Ground tubes	PE	4.4	20.18	3 °C higher
Esquira et al. [66]	Ground tubes	PE	12	46.15	2.5 °C higher
Baille et al. [67]	Ground tubes	PE	5.4	23.37	2–4 °C higher
Pacheco [68]	Ground tubes	PE	15	50	2–4 °C higher
Mercier [69]	Barrels	Glass	4	21.04	10 °C higher
Santamouris et al. [70]	Tanks	Filon	2.25	102.27	16–2 °C > T_{air}
Levav and Zamir [71]	Tanks	PE	40	40	11 °C higher
Sorensen [72]	Barrels	Glass	0.8	66.67	4 °C higher
Fourcy [73]	Tanks	Double glass	1.7	23.61	3 °C higher
Nash and Williamson [74]	Tanks	PE	1	33.33	2–3 °C higher
Santamourise et al. [70]	Tanks	Filon	22	131.73	13–22 °C > T_{air}
Daramarath and Von Zabeltitz [75]	Tanks	Glass	21	91.31	2 °C higher
Farah [76]	Ground tubes	PE	25.6	89.20	2.5–4 °C higher
Campoitti et al. [77]	Tanks	Polycarbonate	5.8	19.33	2–10 °C higher
Grafiadellis [61]	Ground tubes	PE	10	20	2–4 °C higher
Govind et al. [78]	Barrels	PE	3.2	207.79	5–6 °C higher
Dutt et al. [79]	Tanks	PE	1	50	3–4 °C higher
Kozai et al. [80]	Tanks	PE	30.9	36.1	8–10 °C higher
Gupta and Tiwari [62]	Tanks	PE	0.214	10.30	4–6 °C higher
Sethi et al. [81]	Tanks	Glass	1	47.62	4–5 °C higher

Table 3
Summery of the performance of various greenhouses using rock bed as heat storage material.

Reference	Type and mass of rock (kg)	Cover	Total heat capacity[a] of rock (kJ/°C)	Heat capacity of rock per unit m^2 area	Performance
Fotiades [82]	Gravel, 74,000	PE	53,280	177.6	76% heating needs using 1.7 kW fan
Jelinkova [83]	Gravel, 43,000	Glass	30,960	71.67	4–6 °C higher, 400 $m^3 h^{-1}$ flow rate
Brendenbeck [84]	Gravel, not known	Polycarbonate		–	30% heating needs, 60,000 $m^3 h^{-1}$ using 12 fans
Bricault [85]	Gravel, 202,000	PE	145,440	51.03	40% heating cover
Kavin and Kurtan [86]	Bricks, 48,000	PE	48,960	489.6	5500 $m^3 h^{-1}$ flow rate, with 53.4% heat recovery
Santamouris et al. [71]	Pebble, not known	Glass	–	–	3600 $m^3 h^{-1}$ flow rate
Santamouris et al. [71]	Gravel, 13,000	Glass	9360	492.63	10–20 °C higher
Bouhdgar and Boulbing [87]	Gravel, 20,000	PE	14,440	60.17	4–6 °C higher
Arizov and Niyazov [88]	Gravel, 5700	Double PE	4104	102.6	13 °C higher
Santamouris et al. [71]	Gravel, 14,000	Double glass,	10,080	62.16	20% heating needs
Huang et al. [89]	Gravel, 15,700	Glass	11,304	64.22	5 °C higher
Ozturk and Bascetincelik [90,91]	Volcanic 6480	–	–	–	18.9% heating cover

[a] Specific heat (C_p) of gravel, pebble and brick is taken as 0.72, 0.90 and 1.02 kJ/kg °C, respectively.

Benli and Durmus [93]. Levav and Zamir [94] tested $CaCl_2{\cdot}6H_2O$ in greenhouses and reported that the required air temperature in the greenhouse was achieved without any increase in the relative humidity. It was stressed that the most important drawback of the system was the high cost of the PCM. Furthermore, they indicated that the 24 °C melting temperature of the PCM could be high for some crops. Kurklo [122] reported that Kern and Aldrich [95] utilized 1650 kg of $CaC1_2{\cdot}6H_2O$ in aerosol cans each weighing 0.74 kg was used to investigate energy storage possibilities both inside and outside a 36 m^2-ground area greenhouse covered with tedlar-coated. Fibre glass PCM cans were placed in a store with 22.86 mm spacing and two stores containing different amounts of PCM was used, one inside and the other outside the green house. While the energy storage unit inside the greenhouse absorbed the energy of warm air from the ridge of the greenhouse during the daytime, the direction of air flow was reversed for the energy releasing process at night (Fig. 8a).

The energy storage unit outside the greenhouse contained 1376.4 kg PCM and two solar air collectors with 8.55 m^2 surface area each. As the first system, this one also reversed the air flow during energy withdrawal from the store (Fig. 8b). Results of this study showed that, the energy stored by the outside unit was between 105.5 and 158.25 MJ with a solar energy fraction of 38–43%, these were, respectively, 21.1 and 31.65 MJ for the internal unit with a somewhat much smaller solar fraction of 6–8%. Furthermore, it was calculated [96] using the PCM, interior air temperature was maintained 2 °C higher than the outdoor conditions (8.5 °C and 6.5 °C in December and January, 24 h average). $CaCl_2{\cdot}6H_2O$ (3000 kg) was placed in a heat exchanger inside a 200 m^2 glass covered greenhouse situated at Bet Dagan (32.00N 34.49E). Huang et al. [97] had designed and constructed a storage system ($CaCl_2{\cdot}6H_2O$) with two different stacking configurations and air baffling integrated with greenhouse solar system. Cylindrical storage rods were used as the primary storage elements. The result showed that the designed

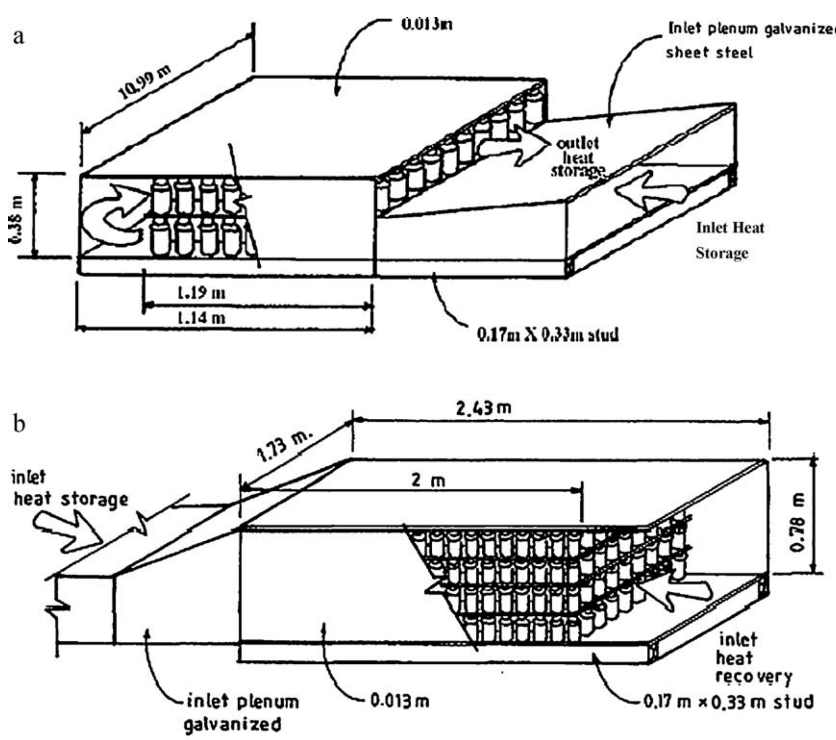


Fig. 8. Thermal storage unit (a) inside and (b) outside the greenhouse [122].

Table 4
Summary of the performance of various greenhouses using different phase change materials.

Reference	Storage medium	Cover material	Quantity of PCM used (kg)	Latent heat capacity of PCM per unit area (kJ/m^2)	Remarks
Paris [100]	NaOH + Cr_2N	Glass	–	–	Gain of 5000 l of oil
Jaffrin and Cadier [98]	$CaCl_2{\cdot}6H_2O$	Glass	13,500	5130	75% cover
Huang and Toksoy [96]	$CaCl_2{\cdot}6H_2O$	Fiberglass	598	1136.2	2 °C higher
Balducci [101]	$CaCl_2{\cdot}6H_2O$	Glass	2800	2660	22% cover
Machida et al. [102]	0.45, $Na_2SO_4{\cdot}10H_2O$/0.45$Na_2CO_3{\cdot}10H_2O$/0.1NaCl	Glass	2500	–	8 °C higher
Huang et al. [97]	$CaCl_2{\cdot}6H_2O$	Fiberglass	1200	2280	5 °C higher
Boulard and Baille [103]	$CaCl_2{\cdot}6H_2O$	Polycarbonate	2970	3206.25	30% cover
Jaffrin and Makhlouf [104]	$CaCl_2{\cdot}6H_2O$	Glass	–	–	51% cover
Brandstetter [105]	$CaCl_2{\cdot}6H_2O$	Glass	100	950	
Boulard et al. [106]	$CaCl_2{\cdot}6H_2O$ + chlorides and nitrates	Polycarbonate	2100	–	7–8 °C higher
Santamouris et al. [71]	$CaCl_2{\cdot}6H_2O$	Glass	3000	2850	–
Ozturk [107]	Paraffin wax	Double, PE	6000	6333.3	40.4% energy efficiency
Benli and Durmus [93]	$CaCl_2{\cdot}6H_2O$	Glass of 5 mm thickness for collectors	300	–	KNO_3 (6 kg) was added into $CaCl_2{\cdot}6H_2O$ to crystallize the PCM

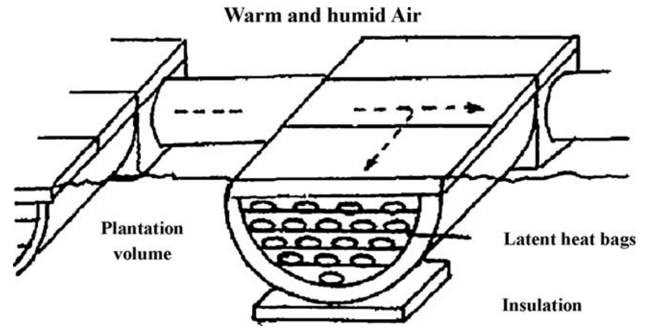


Fig. 9. Air circulation over PCM storage unit in tunnels underground a green house [99].

latent storage systems demonstrated significantly higher compact storage capacity than the rock or water storage Jaffrin and Cadier [98] and by Jaffrin et al. [99] achieved their studies on a single glazed greenhouse for the production of rose with 500 m^2 ground area.

Used 13.5 tons of $CaCl_2{\cdot}6H_2O$ (melting point 28 °C) as a thermal storage material encapsulated in bags arranged on five concrete shelves as shown in Fig. 9 the heated air pass through the shelves, the performance of solar greenhouse compartment with PCM storage was compared with a traditional greenhouse showed that propane gas saved by 80% and 60% in comparison with the conventional and double-covered greenhouses, respectively, latent heat storage material can also be stacked in racks placed in a greenhouse which will be directly heated by the solar radiation [108]. In this system the hot air was circulated in the greenhouse through the storage to increase the rate of charging/discharging of PCM. The stored heat was utilized during off sunshine hours to maintain desired temperature of the green house. $Na_2SO_4{\cdot}10H_2O$ was used as PCM storing material in the green house. Nishina and Takakura [109] used $Na_2SO_4{\cdot}10H_2O$ with some additives to prevent phase separation and degradation for heating a greenhouse in Japan. Fig. 10 shows the general view of the experimental set-up. This study concluded that 40–60% of the latent heat potential of the PCM was realized, which indicated that almost half of the PCM was not used efficiently during the energy exchange processes.

Takakura and Nishina [110] tested polyethylene glycol and $CaCl_2{\cdot}6H_2O$ as PCMs in greenhouse heating for 7.2 m^2 ground area. They compared conventional greenhouses with PCM storage type greenhouses. The efficiency of the greenhouse with PCM storage integrated with solar collector was 59% and able to maintain 8 °C inside the greenhouse at night, when the outside temperature dropped to −0.6 °C. A microcomputer control system has been developed in order to establish more accurate and more sophisticated control for solar greenhouse systems.

In a design and experimentation study by Baille and Boulard [111] and Boulard et al. [106] $CaC_{12}{\cdot}6H_2O$ melting at 21 °C was utilized in a greenhouse with 176 m^2 ground area, double polycarbonate-cover and forced ventilation (Fig. 11). Thermostat settings for night and day in February and March were,

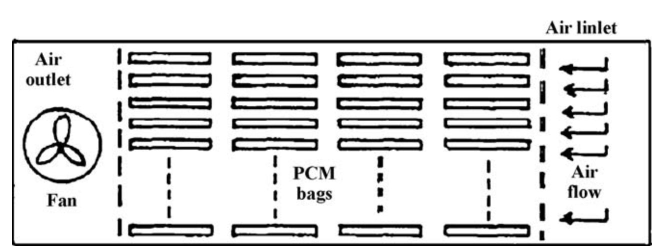


Fig. 10. General view of the phase change energy storage system in green house [109].

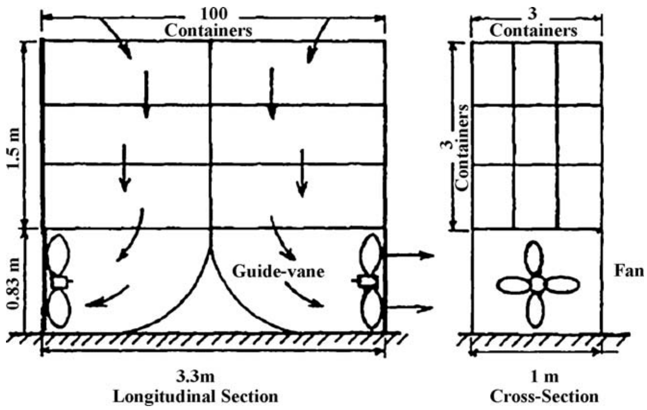


Fig. 11. General view and dimensions of the energy storage unit [111,106].

respectively, 12 and 14, and 22 and 26 °C. Air velocity in the greenhouse had an order of magnitude 1 m/s. It was calculated that while 0.260 kW h/m^2 energy was stored during the daytime, 0.360 kW h/m^2 was released at night in the greenhouse. When the outside air temperatures were 3.8 and 6.6 °C, respectively, in February and March, inside air temperatures for the same periods of 10.9 and 13.5 °C were obtained. With this method, instead of what would be 7.21/m^2 fuel requirement, 40% of heating load was supplied and an overall 30% in energy saving was achieved, these results concluded from Ref. [122].

Ozturk [107] presented a seasonal thermal energy storage using paraffin wax as a PCM with the latent heat storage technique was attempted to heat the greenhouse of 180 m^2 floor area. The schematic arrangement of the LHS system for greenhouse of 180 m^2 floor area. The schematic arrangement of the LHS system for greenhouse heating is given in Fig. 12. The system consists mainly of five units: (1) 27 m^2 flat plate solar air collectors, (2) 11.6 m^3 latent heat storage unit stored in tank, (3) experimental greenhouse, (4) heat transfer unit and (5) data acquisition unit. The LHS unit was filled with 6000 kg of paraffin, equivalent to 33.33 kg of PCM per square meter of the greenhouse ground surface area. Energy and exergy analyses were applied in order to evaluate the system efficiency. During the experimental period, it was found that the average net energy and exergy efficiencies were 40.4% and 4.2%, respectively.

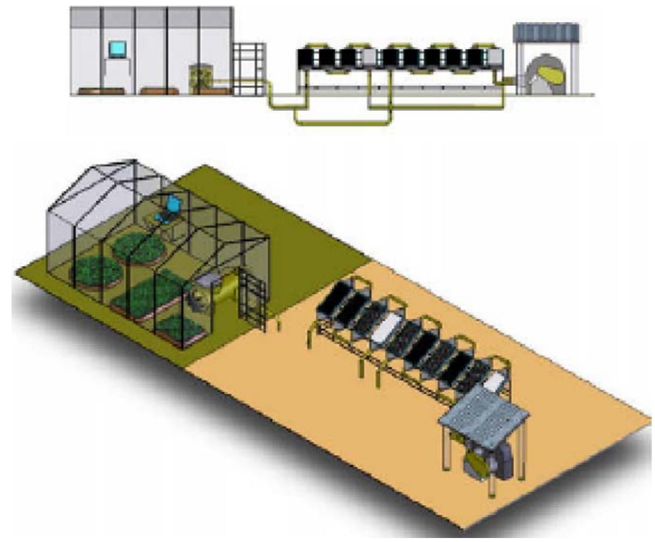


Fig. 13. Views of experimental equipment of greenhouse heating system; front and isometric [112,93].

The effect of the temperature difference of the heat transfer fluid at the inlet and outlet of the LHS unit on the computed values of the energy and exergy efficiency is evaluated during the charging period.

Benli [112] studied heat distribution in a greenhouse which has built in Turkey using solar air collector face profiles and phase change material (calcium chloride hexahydrate as the PCM) (Fig. 13) and studied with Benli and Durmus [93] analytically and experimentally to evaluate the thermal performance of five types of ten pieced solar air collectors and PCM, under a wide range of operating condition as shown in Fig. 13.

The solar air collectors and PCM system created 6–9 °C temperature difference between the inside and outside the greenhouse. The proposed size of collectors integrated PCM provided about 18–23% of total daily thermal energy requirements of the greenhouse for 3–4 h, in comparison with the conventional heating device.

Najjar and Hasan [113] were developed a mathematical model for temperature of phase change material, solution of this model compared with experimental results. The PCM is incorporated in

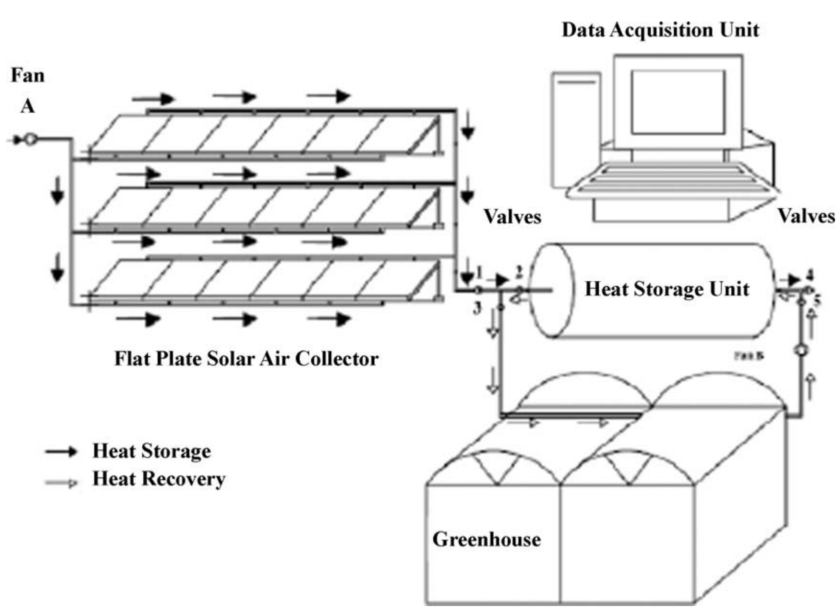


Fig. 12. Solar air collector used with PCM [107].

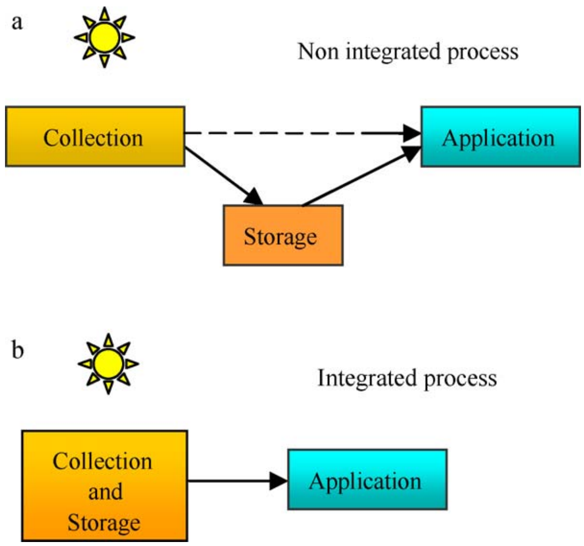


Fig. 14. the process of thermal energy collection and storage in two methods.

a greenhouse model the combined greenhouse model and PCM models are solved in order to determine the inside greenhouse air temperature. Including the PCM energy storage inside the greenhouse can decrease the maximum air temperature difference during 24 h by 3–5 °C. This narrowing of temperature inside the greenhouse can be further improved by enhancing the convection heat transfer between the PCM storage and air inside the greenhouse.

5. Solar air heaters integrated with storage material

The thermal loss increasing when the process length increases as shown in Fig. 14, this is similar to the direct proportional between the length of wire to it is resistance in the electricity laws, so in case of non-integrated system, it is need more insulation and more space consequently, more cost to the system. The maintenance for non-integrated system is higher cost than that for integrated one because, the stages and the system constituents is more for the first one. For these concerns many researchers studied the solar air heaters integrated with storage material.

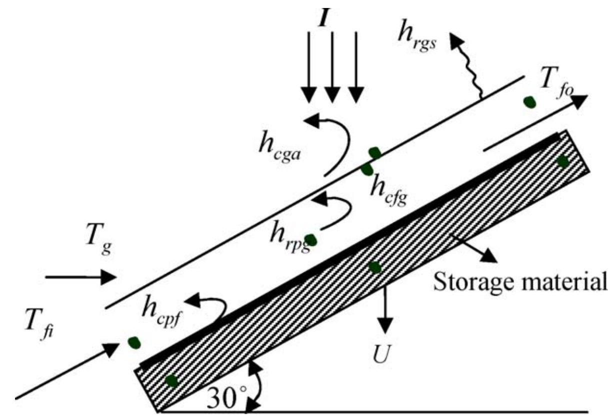


Fig. 16. View of air heater with storage material [115].

Fatah [114] developed a simple solar air heater integrated with thermal energy storage system as shown in Fig. 15. A set of copper tubes were filled with thermal energy storage material and placed as an absorber. Different sensible heat and latent heat storage materials were studied. The results indicated that the heater filled with PCMs with 51 and 43 °C melting temperatures gives the best performance; otherwise the system daily average efficiency varies between 27% and 63%. Depending on the PCM melting temperature, solar intensity and system air flow resistance.

Aboul-Enein et al. [115] studied an inclined solar air heater with and without thermal storage for crop drying as shown in Fig. 16. The air heater is designed to be able to insert various storage materials under the absorber plate in order to improve the drying process. Sand, granite and water were used as the storage material. The results indicate that; the average temperature of flowing air proportional directly with collector length, and width until typical values for design parameters. The outlet temperature of flowing air proportional inversely with the gap spacing and mass flow rate, the thermal performance of the air heater with sensible storage

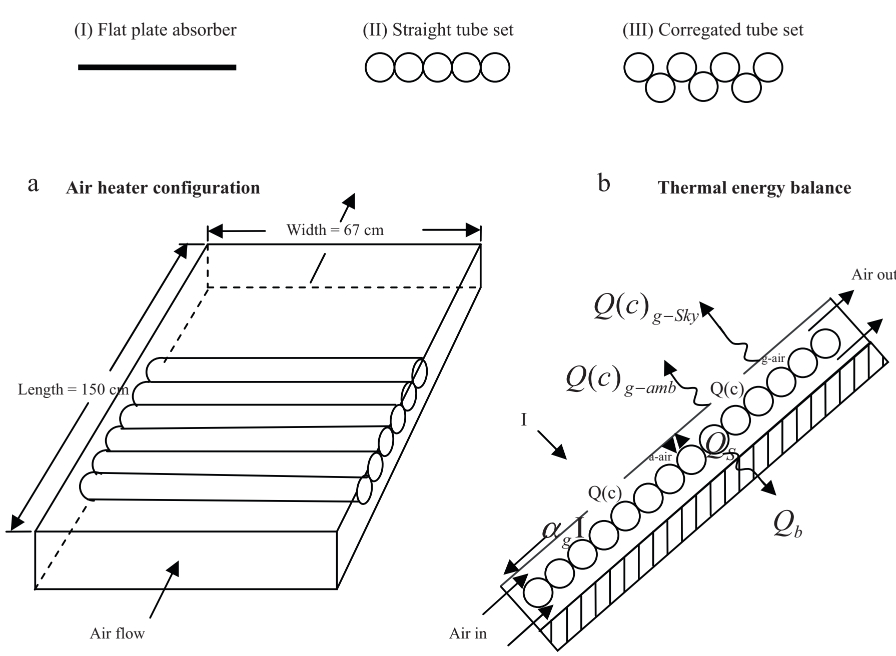


Fig. 15. Solar air heater integrated with PCM [114].

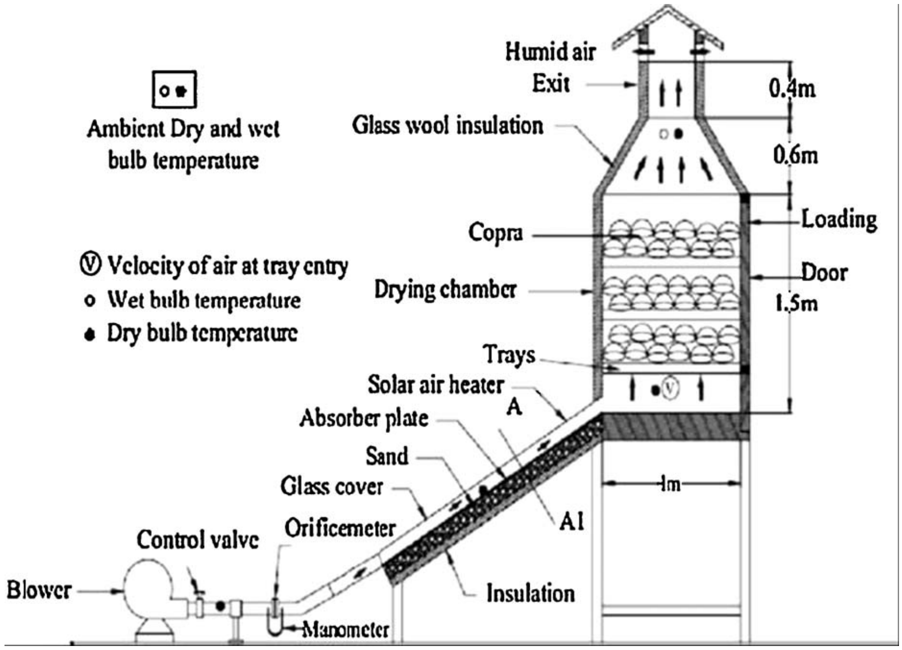


Fig. 17. Schematic of solar air heater integrated with storage unit used for copra drying [116].

material higher than that when no storage and the optimum thickness of the storage material is about 0.12 m. Mathematical model achieved for the thermal performance of the air heater.

Mohanraj and Chandrasekar [116] performed an indirect forced convection solar drier integrated with heat storage material, it was designed, fabricated and investigated for copra drying as shown in Fig. 17. To increase the temperature of air by green house effect, a glass cover of 5 mm thickness was placed. The gap between the glass and the absorber surface was maintained at 25 mm for air circulation. One side of the collector was connected to the blower with the help of reducer and the other side was attached with drier cabin. The 100-mm gap between the absorber and insulation was filled with sand mixed with aluminum scraps to store the heat during sunshine hours and to obtain hot air during off sunshine hours.

The drier with heat storage material enables off sunshine hours. The drier with heat storage material enables to maintain consistent air temperature inside the drier. The experiments with heat storage material were conducted for 8 h during potential sunshine hours and 4 h during lean or off sunshine hours The chili was dried from initial moisture content 72.8% to the final moisture content about 9.2% and 9.7% (wet basis) in the bottom and top trays, respectively. It could be concluded that, forced convection solar drier is more suitable for producing high quality dried chili for small holders. Thermal efficiency of the solar drier was estimated to be about 21% with specific moisture extraction rate of about 0.87 kg/kWh. Madhlopa and Ngwalo [117] designed, constructed and evaluated an indirect type natural convection solar dryer with integrated collector–storage solar and biomass-back-up heaters as shown in Fig. 18.

Enibe [118] constructed and studied a natural convection solar air heater with phase change material (Fig. 19), energy storage used the paraffin wax as a PCM, under natural environmental conditions involving ambient temperature variations in the range 19–41 °C and daily global irradiation in the range 4.9–19.96 MJ/m^2. Peak temperature rise of the heated air was about 15 K, while peak cumulative useful efficiency was about 50%. This system has been designed to use as a solar cabinet crop dryer or poultry egg incubator. Enibe [119] studied the transient thermal analysis of the previous design. The heated air and glazing surface were predicted to within 10 °C. The maximum predicted airflow rate was 0.01 kg/s, corresponding to a maximum inlet velocity of 0.33 m/s. The performance evaluation of a tilted multi-pass solar air heater with in-built thermal storage has been carried out for deep-bed drying applications as shown in Fig. 20 [120]. The grain temperature increases with the increase of collector length, breadth and tilt angle up to typical value of these parameters, the thermal energy storage also affect during the off-sunshine hours is very pertinent for crop drying applications. The proposed mathematical model is useful for evaluating the thermal performance of a flat plate solar air heater for the grain drying applications. It is also useful to predict the moisture content, grain temperature predict the moisture content, grain temperature, humidity of drying air and drying rate in the grain bed (Fig. 20).

Alkilani et al. [58] achieved indoor prediction for output air temperature due to the discharge process in a solar air heater integrated with a PCM unit (Fig. 21), for eight different values of mass flow

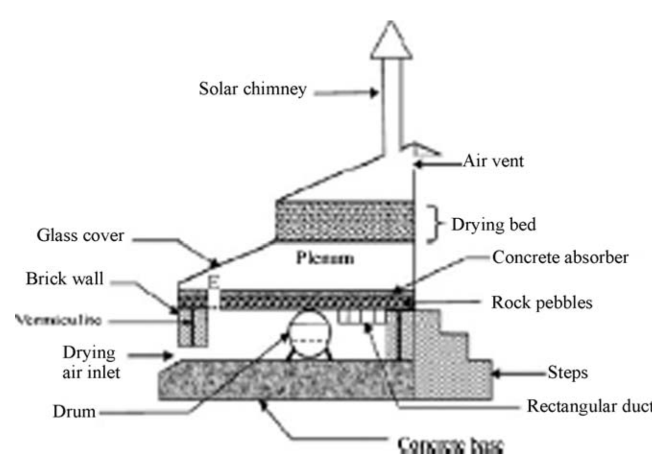


Fig. 18. Cross-sectional view of the solar dryer through the burner, collector, drying chamber and solar chimney [117].

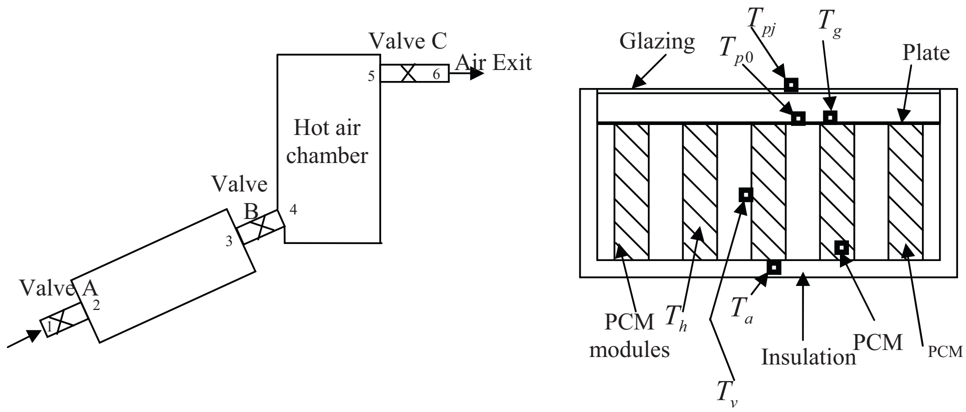


Fig. 19. Schematic view of a natural air heater with cross-sectional view show the PCM [118].

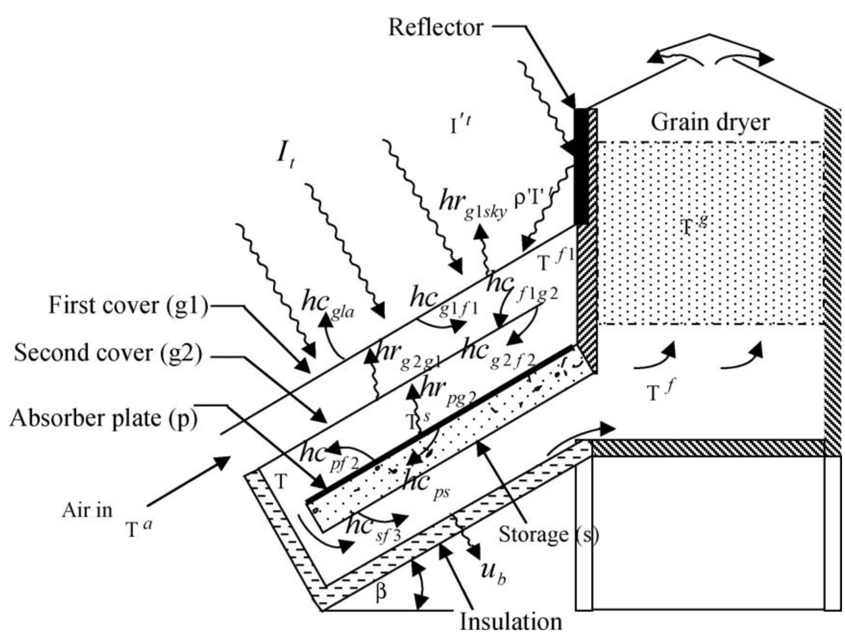


Fig. 20. Multi-pass solar air heater integrated with storage unit used for drying application [120].

rate, and reached the maximum output air temperature 42 °C, with mass flow rate 0.05 kg/s. The PCM consists of paraffin wax with mass fraction 0.5% aluminum powder to enhance the heat transfer, the freezing time for the PCM unit was predicted for each mass flow rate, The freezing time of the PCM cylinders related inversely to the mass flow rate, and take longer time approximately (8 h) with flow rate of 0.05 kg/s.

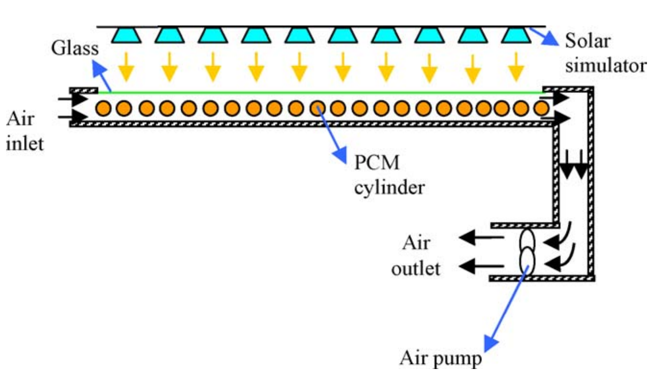


Fig. 21. Single-pass solar air heater integrated with PCM unit [58].

6. Conclusion

A review of solar air heating systems with storage units include space heating systems, greenhouses with various thermal storage materials, solar air heaters integrated with various storage materials and heat transfer studies on air as a heat transfer fluid, have been carried out. We conclude from this study that the recent researches focused on the phase change materials (PCMs) as a storage materials, because of the higher thermal energy storage density of these materials in contrast of sensible heat storage materials. For a better thermal performance of solar air heater a phase change material with high latent heat and with large surface area for heat transfer is required. The researcher's designs going to the integration between solar energy collection and thermal storage to reduce the heat loss, volume and system cost.

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